

X-RAY VARIABILITY OF AGN AND CORRELATIONS WITH SPECTRAL PROPERTIES

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ABSTRACT

Rapid flux changes in the X-ray emission from active galactic nuclei are commonly observed. The power-density spectra show a pseudo power-law form with a turnover at low frequencies and a high frequency break, similar to galactic black-hole candidates. There have been a few claims for periodicities but these are not a well-established property of the class. The amplitude of variability depends on a number of source parameters, including luminosity and spectral properties. The variability amplitude is correlated with X-ray spectral index, and anti-correlated with the width of the permitted optical lines. In one particularly well-observed case, NGC 7469, we see a relationship between the X-ray and UV variability, which indicates that the dominant emission process for the X-rays is thermal Comptonization. Variations in the X-ray emission are related to changes in the UV seed photons, but it appears there must also be a mechanism - perhaps that which heats the Comptonizing corona - that induces rapid variability intrinsic to the X-rays.

INTRODUCTION

Active Galactic Nuclei (AGN) ¹ show large-amplitude, rapid variability in the X-ray band, which has been taken as evidence that the X-rays come from very close to the central black hole. The mechanism producing these variations remains mysterious, however. The X-rays in AGN are thought to be produced by Compton upscattering of softer photons in a hot “corona” (e.g. Sunyaev & Titarchuk 1980). Such models fit the X-ray spectrum extremely well (Haardt & Maraschi 1991, 1993), particularly if the corona is patchy (Haardt, Maraschi & Ghisellini 1994; Stern et al. 1995) and the particle distribution has a thermal form (Zdziarski et al. 1994; Madejski et al. 1995; Gondek et al. 1996). The coronal heating mechanism is not known, but some possibilities are that a portion of the accretion flow is intrinsically hot (e.g. Shapiro, Lightman & Eardley 1976; Narayan & Yi 1994) or that magnetic reconnection creates hot flaring regions above an accretion disk (e.g. Nayakshin & Melia 1997; Poutanen & Fabian 1999). In either case, any variations in the “seed” photons for the Comptonizing medium would be mimicked in the X-ray band inducing X-ray variability. It has always appeared that the most rapid variations occur in the X-ray band, however, which is not consistent with the variability being merely a secondary effect, and suggesting some other variability mechanism associated with the coronal dissipation process. Progress in understanding these phenomena can be made by accumulating high quality data on the X-ray variability and comparing these in more detail to Comptonization and other models, and to other properties of the AGN.

X-RAY VARIABILITY CHARACTERISTICS OF AGN

EXOSAT demonstrated rapid variability in a number of AGN (e.g. Lawrence et al. 1985; McHardy & Czerny 1987) and allowed the first definition of their Power Density Spectrum (PDS). Lawrence & Papadakis (1993) and Green, McHardy & Lehto (1993) performed systematic analyses of the EXOSAT data. Both sets of workers generally found a featureless PDS with a steep “red noise” power-law characterizing the variations. For an assumed form for the power of $P(f) = Af^{-\alpha}$, where A is the normalization, all objects

¹Here we restrict our discussion to radio quiet AGN, which make up the majority of the population. Radio-loud AGN, in particular jet-dominated blazars show extreme variability, particularly in the γ -rays, but are atypical in this regard

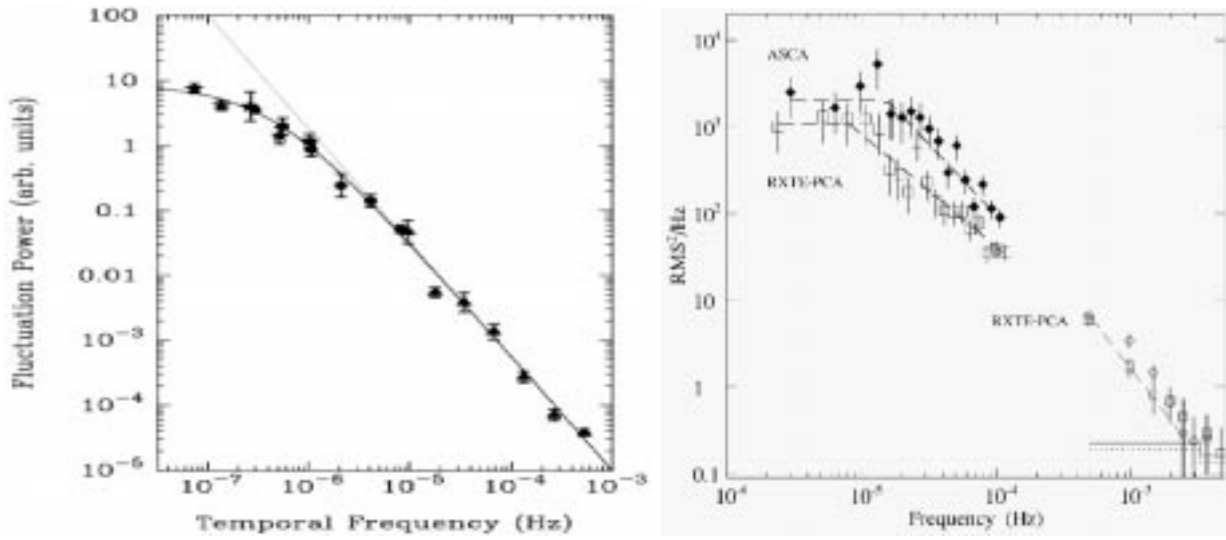


Fig. 1. (left panel) PDS of NGC 3516 obtained by the *RXTE* PCA instrument (Edelson & Nandra 1999). The source was sampled on time scales ranging from minutes to years. This clearly shows a knee at low frequencies, and exhibits a characteristic time scale of about 1 month. (right panel) PDS of MCG-6-30-15 (Nowak & Chiang 2000) obtained by *RXTE* and *ASCA*. The low frequency knee is visible here also, but there also appears to be a break at higher frequencies. Both PDS are reminiscent of Cyg X-1.

were consistent with a single slope of $\alpha = 1.5$. This steep slope indicates that there must be a turnover (that will henceforth be termed the “knee”) at low frequencies, or the integral power would be infinite. Early attempts at finding this knee (e.g. Papadakis & McHardy 1995) have now been improved upon using *RXTE* data, and there are now several convincing reports (e.g. Fig. 1; Table 1; McHardy et al. 1998; Edelson & Nandra 1999; Chiang et al. 2000). The knee frequencies indicate characteristic time scales of orders days-months. There has also been the report in at least one case of a high frequency break, with the PDS of Seyfert MCG-6-30-15 showing a further steepening above a frequency of $\sim 10^{-3} - 10^{-4}$ Hz (Fig. 1; Nowak & Chiang 2000). The general form of the PDS immediately brings to mind that of Cyg X-1 (e.g. Belloni & Hasinger 1990), which exhibits “white noise” ($\alpha = 0$) variability below the knee, steepening to $\alpha = 1$ and then to $\alpha = 2$ above the high frequency break.

Lawrence & Papadakis (1993) first showed that the normalization of the PDS at a fixed frequency was inversely dependent on the luminosity. This dependence has also been confirmed by more recent data (e.g. Fig. 2; Nandra et al. 1997). This and the similarity with Cyg X-1 suggests there may be a “universal” PDS - and variability mechanism - for accreting black holes, which scales with some quantity like the mass or luminosity of a given object. Table 1 shows a general trend of decreasing break frequency with luminosity, and indeed it seems more intuitive to associate the differences in variability characteristics to changes in time scale, rather than in amplitude. Higher luminosity objects presumably have higher masses, and correspondingly larger size scales. Objects that turn over at longer time scales would tend to show less variability at fixed frequencies above the knee.

The work of Markowitz & Edelson (2000) has lent strong support to this idea that the “universal” PDS scales in frequency, rather than amplitude. These workers showed that the luminosity dependence of variability amplitude is also a function of the time scale sampled. A shallower dependence of the variability amplitude with luminosity is seen on long (\sim yr) time scales, compared to \sim day time scales. They also found less scatter in the former relation. This can be interpreted in the framework of the universal PDS where the form shifts along the frequency axis of the PDS plot. On long time scales, we expect similar power in all objects, as we are sampling white noise variability below the knee of the PDS, accounting for the shallower relationship with luminosity. At high frequencies, above the knee, there would be stronger relationship. Subtly different shapes above the knee and the differing effect of the high frequency break would cause more

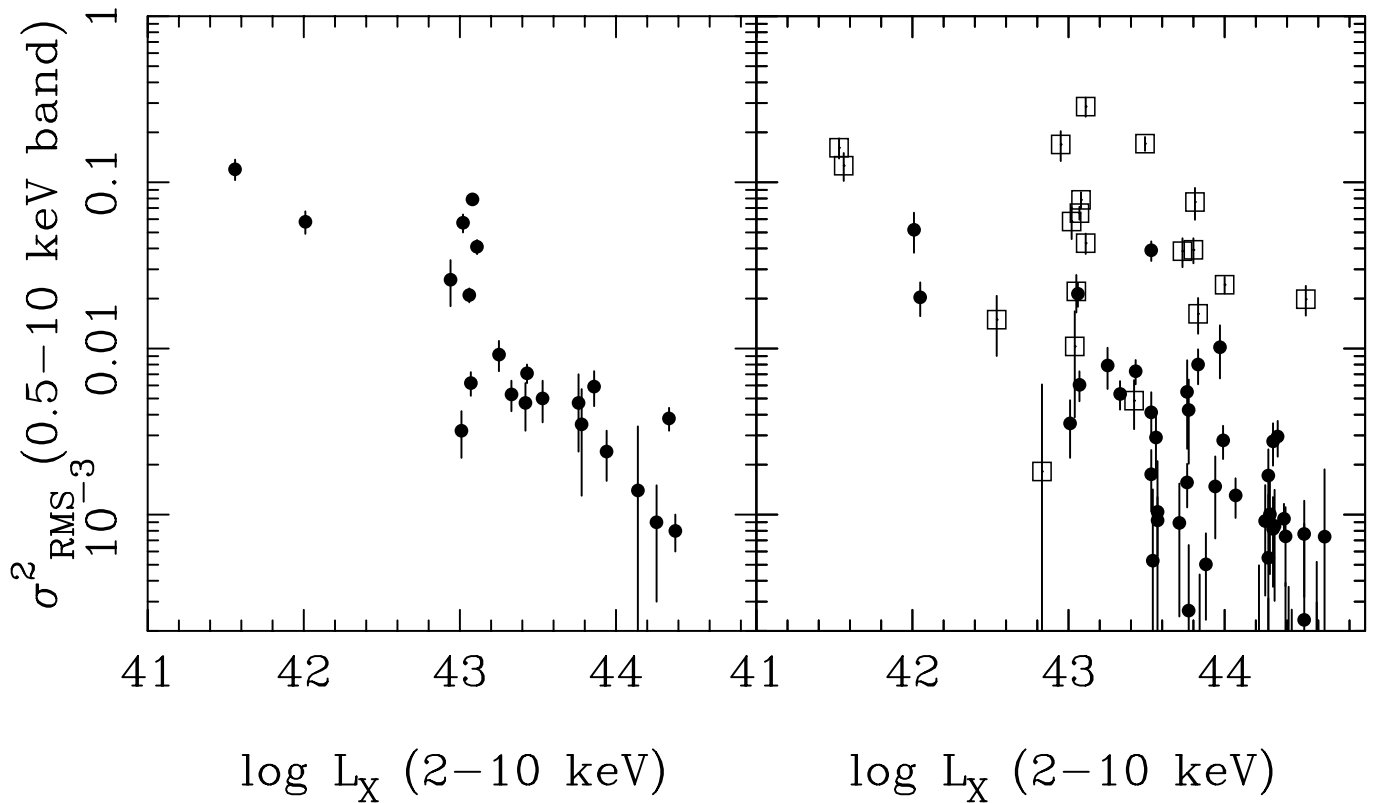


Fig. 2. Dependence of the variability amplitude (parameterized by the “excess variance”) with luminosity for a sample of “normal” Seyfert galaxies (left panel; Nandra et al. 1997). The variability amplitude shows a strong anticorrelation. The right panel shows the extended sample of Turner et al. (1999), which contains many more NLS1, shown as the open squares in that panel. These tend to show a higher variability amplitude for a given luminosity, supporting the idea that they have higher accretion rates than “normal” Seyfert 1s

scatter also.

This apparent scaling of PDS shape with luminosity appears to break down at the lowest luminosities, however, with the least powerful AGN showing less pronounced variability at least on short time scales (e.g. Ptak et al 1998). This may indicate that this type of AGN has a relatively large mass (e.g. Iyomoto & Makishima 2000), but a different emission mechanism and accretion mode, such as a radiatively inefficient flow (e.g. Narayan & Yi 1994; Blandford & Begelman 1999). If there is a universal PDS scaling with mass, rather than luminosity, then it is in principle possible to determine the mass from the variability properties by scaling from Galactic black hole candidates (GBHC) such as Cyg X-1 (e.g. Hayashida et al. 1998). Although much recent progress has been made, we will need far better data on the PDS of AGN before such estimates can be considered robust. Uncertainties in our knowledge of the mass of Cyg X-1, and variability of its noise characteristics (Belloni & Hasinger 1990) introduce further limitations to such methods.

No consensus has emerged as to the physical interpretation of either the low frequency knee or the high frequency break. These features are presumably related either to a physical size in the system or to some characteristic time scale in the accretion disk. Examples of models that have attempted to describe the PDS shape are those with extended, inhomogeneous coronae (Kazanas, Hua & Titarchuk 1997; Hua et al. 1997), magnetic flares (Poutanen & Fabian 1999) and self-organized criticality (Mineshige et al. 1994).

Periodicities

Mass-measurement through variability would be considerably eased if there were precise periodicities that could be compared between objects. Unfortunately such periodicities have been very difficult to pin down.

Table 1. Measurements of the low-frequency knee in accreting black holes

Object	$\log L_X$ (erg s ⁻¹)	ν_{br} (Hz)	Reference
NGC 5548	44.0	6×10^{-8}	Chiang et al. (2000)
NGC 3516	43.4	4×10^{-7}	Edelson & Nandra (1999)
MCG-6-30-15	43.0	8×10^{-6}	Nowak & Chiang (2000)
NGC 4051	41.6	5×10^{-5}	McHardy et al. (1998)
Cyg X-1	37.0	$4 - 40 \times 10^{-2}$	Belloni & Hasinger (1990)

The analogy with GBHC suggests that AGN might well exhibit quasi-periodic oscillations (QPOs), and there were some reports of periodic behavior from EXOSAT and Ginga (e.g. Papadakis & Lawrence 1993, 1995), with the most famous case being NGC 6814 (Mittaz & Branduardi-Raymont 1989; Done et al. 1992). One case has been disputed (Tagliaferri et al. 1996) and the the periodicity in NGC 6814 has been refuted decisively (Madejski et al. 1993). There are remaining claims in NGC 4051 (Papadakis & Lawrence 1995), RX J0437.4-4711 (Halpern & Marshall 1996) and IRAS 18325-5926 (Iwasawa et al. 1998). Given the difficulties in analysis of AGN power spectra – mainly associated with the severe distortion of most PDS by the window function – and the controversy surrounding the claims of periodicities, many workers have been reluctant to accept the contention that AGN exhibit any periodic behavior. Further data will resolve this issue, which remains open.

CORRELATIONS WITH SPECTRAL PROPERTIES

Green et al. (1993) first showed that the PDS of Seyferts depends on the spectral shape, in that sources with steeper power-law slopes appeared to be more variable on short time scales. This results has now been confirmed by ROSAT and ASCA studies (Fig. 3; Koenig, Staubert & Wilms 1996; Fiore et al. 1998; Turner et al. 1999). Green et al.’s original explanation of this behavior was that the harder sources have a more dominant contribution from “Compton reflection”, although this seems unlikely given the relatively small contribution that reflection makes in the $\sim 2 - 6$ keV band to which the EXOSAT data were most sensitive.

New impetus for the study of this correlation has arisen from the realization that many of the properties of active galaxies are inter-related. Boroson & Green (1992) showed numerous optical line widths and strengths showed correlations, most notably $H\beta$ width and Fe II strength, and identified a driving parameter “eigenvector 1” through principal component analysis. Boller et al. (1996) brought the X-rays into this picture, by showing that the soft X-ray spectral index of AGN is also correlated with $H\beta$ width. These observations have concentrated much attention on the the subclass of AGN known as “Narrow-Line Seyfert 1” (NLS1) galaxies, which exhibit the narrowest permitted (specifically $H\beta$) lines, strongest Fe II emission and steepest X-ray slopes. Some NLS1 were also shown to have dramatic X-ray variability properties in ROSAT observations (e.g. Boller et al. 1997), fitting in with the correlation of X-ray slope with variability amplitude just described.

Turner et al. (1999) demonstrated explicitly the correlation between X-ray variability amplitude and FWHM $H\beta$ (Fig. 3). Leighly (1999) has shown similar results, by showing that the NLS1 occupy a particular part of the σ_{RMS}^2 vs. luminosity diagram (also demonstrated in Fig. 2). These observations show that X-ray variability amplitude can be added to the slew of correlated properties related to “eigenvector 1”. This is of clear importance, as X-ray variability must be related to some fundamental energy-generation process. The current wisdom is that that NLS1 have lower masses and higher accretion rates than objects with broader optical lines (Pounds et al. 1995). The higher variability amplitude in NLS1 fits into this picture, as they would be smaller than broad-line objects at the same luminosity. Many of the details are unclear, however, given that the origin of the variability - and even of the X-rays themselves, is not very well known. For instance, the steeper slopes observed in NLS1 clearly show that their Comptonizing coronae have different physical characteristics. This could result in differing variability characteristics, even at the same mass.

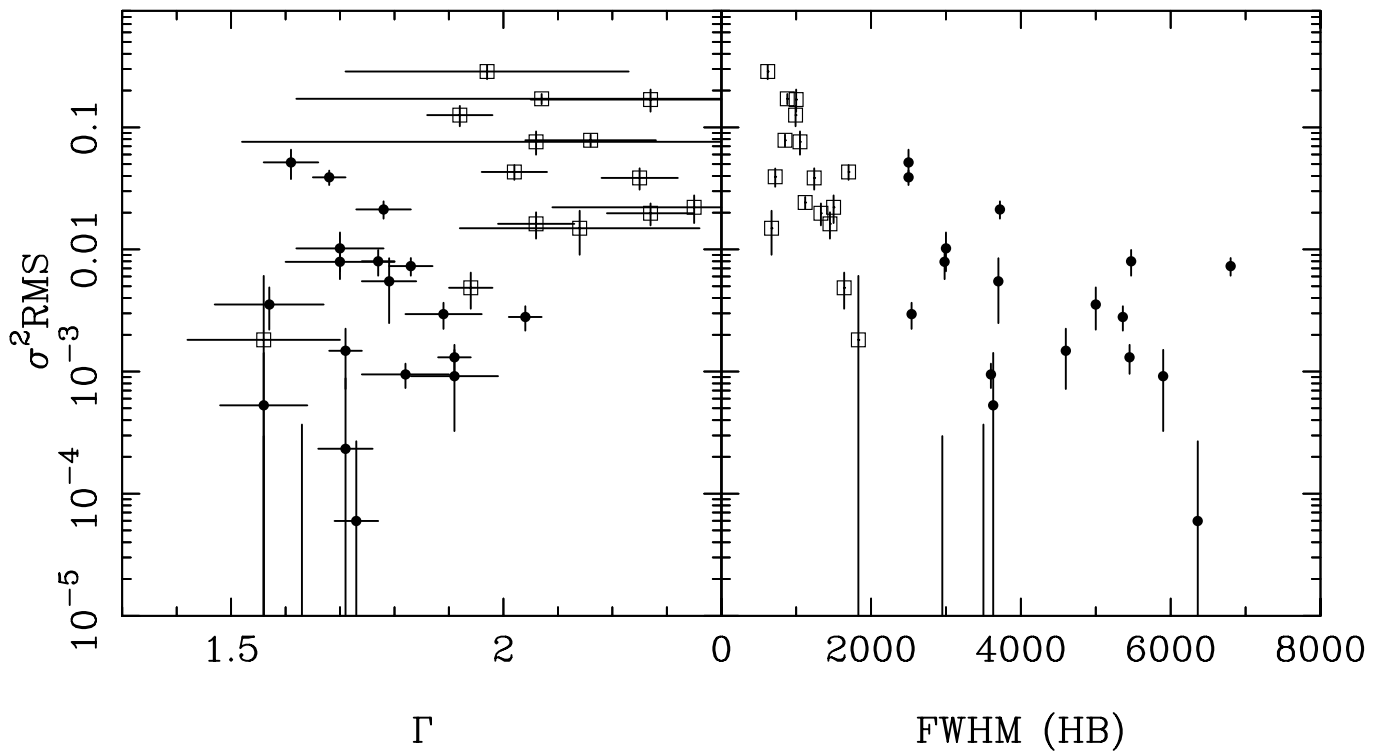


Fig. 3. Dependence of the excess variance on (left panel) the X-ray spectral index derived in the 2-10 keV band and (right panel) the FWHM of the optical $H\beta$ line (adapted from Turner et al. 1999). A weak, positive correlation is seen in the first case, and a very strong anticorrelation is observed in the latter.

NGC 7469: A variability case study

RXTE undertook a long (~ 30 d), quasi-continuous monitoring observation of the Seyfert 1 galaxy NGC 7469, simultaneously with IUE (Nandra et al. 1998, 2000). RXTE showed strong variations in the X-ray flux. The UV flux also varied (Wanders et al. 1997), but the most rapid changes seen in the X-rays were not present in the UV light curve. The fluxes in the 2-10 keV band and 1315Å bands were not well correlated, which contradicts naive expectations from the Compton upscattering models that identify the UV as the seed photons. The lack of a clear relationship is also counter to simple “reprocessing” models for the UV emission, which will not be discussed in detail here, but have many attractive features.

The apparent discrepancy between the data and these model is explained when the *RXTE* spectral data are taken into account (Fig. 4). This shows that, although the 2-10 keV and UV fluxes are not well correlated, there is a very strong relationship between the UV flux and the X-ray spectral index (measured in the 2-20 keV band; Fig. 5). This is expected in Comptonization models: as the UV seed flux increases so does the cooling, resulting in a softer spectrum (e.g. Haardt, Maraschi & Ghisellini 1997; Zdziarski, Lubinski & Smith 1999). The lack of correlation between the UV seed photons and the 2-10 keV X-ray flux may then be explained by a bandpass effect, with the 2-10 keV flux being strongly affected by the X-ray spectral variations. Extrapolation of the X-ray power law over a wider band shows that both the soft X-ray/EUV flux and the broad-band X-ray photon flux (Fig. 5) are both well correlated with the UV emission. The former is helpful for the reprocessing models. The latter is indeed what might be expected in the Comptonization scenario, in the sense that the correlation should be between the photons, and not necessarily the flux. An increase in the number of seed photons results in a corresponding increase in the number of X-ray photons, but the total energy output in a relatively narrow spectral band also depends on other factors, such as the optical depth, temperature and energy input into the corona. The NGC 7469 spectral data therefore offer strong support for the Comptonization model. Correlations have been observed between the UV and EUV emission in at least one Seyfert (Marshall et al. 1997) and between the EUV and the X-ray emission (Uttley

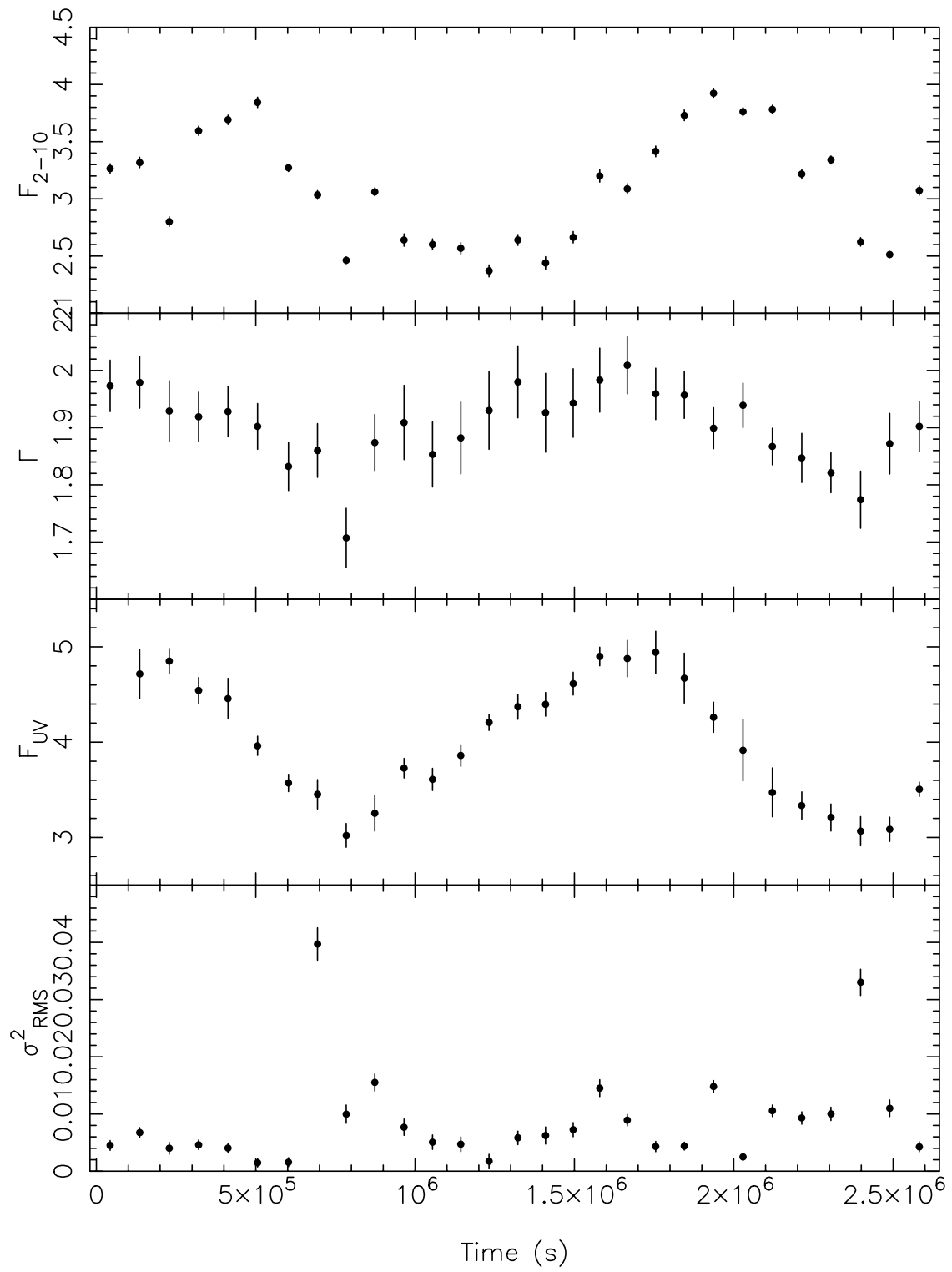


Fig. 4. Light curves for NGC 7469 of (top to bottom) the 2-10 keV X-ray flux (F_{2-10}), the X-ray spectral index (Γ), the ultraviolet 1315Å flux (F_{UV}) and the fractional excess variance computed on time scales of 1 day (σ_{RMS}^2). The spectral index is not well correlated with the X-ray flux, but follows the UV flux (see also Fig. 5). This is supportive of thermal Comptonization models. The excess variance shows unusual behavior, with periods of significantly enhanced variation apparently coinciding – or perhaps preceding by ~ 1 d – the times where the X-ray spectrum is hardest and the UV flux weakest. The reason for this behavior is unclear, but it may represent some kind of instability in the system.

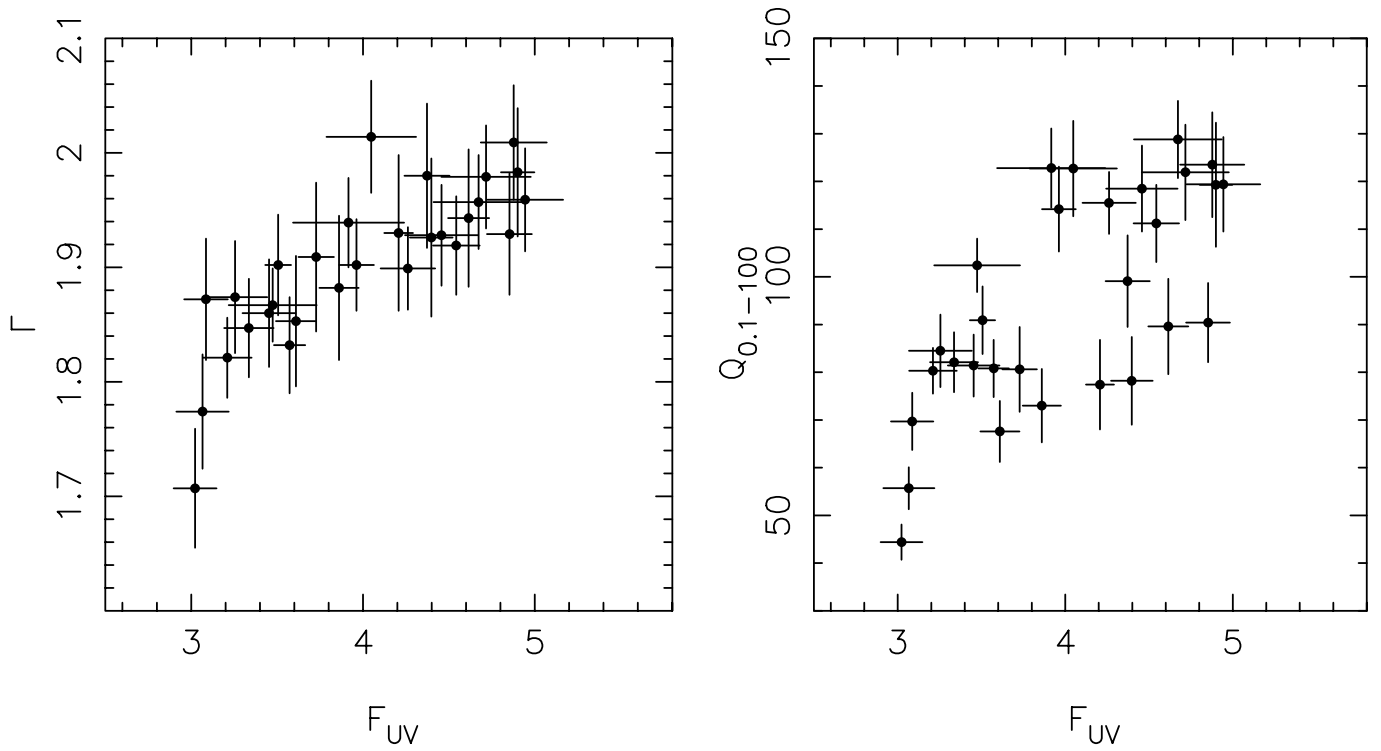


Fig. 5. The left panel shows the correlations between the UV flux of NGC 7469 at 1315\AA and X-ray spectral index (Γ). There is a strong correlation, as expected in Comptonization models if the UV represents the seed photons. Increased seed flux would cool the X-ray Comptonizing corona, resulting in a steeper slope. The right panel shows the relationship between the UV flux and the broad-band (0.1-100 keV) X-ray photon flux. This strong correlation again supports Comptonization, as we expect in such models that one scattered UV photon would ultimately emerge as an X-ray, although we note that a narrow band might not show such a correlation (c.f. Fig. 4).

et al. 2000). The latter may even show a time delay in the sense that the EUV emission leads (Chiang et al. 2000), further supporting the Comptonization hypothesis. Finally, a long BeppoSAX observation of NGC 5548 showed an explicit connection between the spectral slope in the X-ray band and the high energy cutoff, which indicates the temperature of the corona (Petrucchi et al. 2000). During a “flare” in the X-ray emission, the X-ray spectrum was seen to steepen and the temperature to reduce, exactly as expected from the thermal Comptonization models if the UV also increased during the flare. Unfortunately no UV data were available at the time of the BeppoSAX observation, but combining the results with those obtained for NGC 7469 leads to compelling evidence that thermal Comptonization is indeed the dominant radiation mechanism producing X-rays in radio quiet AGN.

The fact that the X-rays show much more rapid variations than the UV is, on the other hand, inconsistent with a simple picture in which energy is dissipated in the Comptonizing corona at a constant rate, and variations in the UV seed photons cause both the X-ray variability and cooling of the corona. In this case, as the X-rays are a secondary component, they should vary less rapidly than the seed photons, or with a lower amplitude on a fixed time scale. There are at least two ways around this that preserve the Comptonization model. First, the UV may not be the seed photon population, but may merely be correlated with the true seed, presumably the EUV coming from smaller radii. This could then be more rapidly variable than both the X-rays and the UV, but have the variations more smoothed in the UV than the X-rays. Second, the very rapid X-ray variations might arise from a process unrelated to the Compton seed, most obviously the coronal heating mechanism.

The PDS appears to resolve this ambiguity (Nandra & Papadakis 2001; Fig. 6). There is no obvious low

frequency knee down to a frequency of about 10^{-6} Hz, which is not surprising given the luminosity is rather similar to NGC 3516 (Fig. 1), where the knee is an order of magnitude lower in frequency. These time scales were not sampled by the NGC 7469 campaign. Fig. 6 shows the PDS obtained at three different energies. There are no obvious features in any, although at high frequency the PDS do show some structure that is not well fit by the power-law model. The most striking thing about Fig. 6, however, is the clear difference in the power spectra as a function of energy. At low frequencies there is clearly more power in the soft X-ray PDS, but the opposite is true at high frequencies. This is parameterized in the bottoms panel of the Figure by a power law that is significantly flatter at higher energies. Although the signal-to-noise ratio in the 10-15 keV band is lower than the softer energy bands, making it more susceptible to errors in the background subtraction, these are unlikely to cause the observed effect. A similar analysis of “blank sky” background observations reveals no such effect, nor any excess of power at high frequencies which might bias our results. It is interesting to note that a similar behavior “hardening” of the PDS has been reported for Cyg X-1 (Nowak et al. 1999) and is very much opposite to that expected from Comptonization (e.g. Hua & Titarchuk 1996) where the PDS should be steeper at high energies. High energy photons undergo more scatterings, “washing out” the high frequency variability.

The implication is that the most rapid variations are not caused by variations in the Compton seed - regardless of whether the seed photons are UV or EUV - but arise from a separate mechanism. We identify this with the process that heats the X-ray corona (for example, the magnetic flares of Poutanen & Fabian, 1999, although they predict the high frequency power spectrum should be similar at all energies). Assuming that the X-rays are indeed produced by Compton upscattering, it seems highly unlikely that this “hardening” can be produced in a model where the X-rays are produced in a single, coherent region. In such a scenario, changes in the dissipation rate would presumably affect all energies in the same way. Our data require a patchy corona, or localized “flares”. One possibility is that the flares in the inner regions are typically hotter. They would therefore account for more of the high energy photons, but be more rapidly variable because of their smaller size scale. We await a detailed model that explains this flattening of the PDS with increasing photon energy, which appears to be relevant to both GBHC and, now, AGN.

A final intriguing result from the NGC 7469 campaign is illustrated by the bottom panel of Fig. 4. This shows the fractional RMS variability observed in the $\sim 1d$ integrations used to derive the spectral parameters. The variability amplitude clearly changes from day to day. Most dramatically, it seems to show a strong increase at the times (or perhaps just preceding the times) when the UV flux is weakest and the X-ray spectrum the hardest. The behavior of this object thus contrasts with that when comparing objects (Fig 3; sources with flat spectra are *less* variable on $\sim d$ time scales). The reason for this is not clear at this point, but it may be related to some form of instability in the corona. For example, as the spectrum hardens it may reach a critical point at which electron-positron pair production becomes important, inducing additional variability.

SUMMARY

Variability studies of AGN have been somewhat neglected since the *EXOSAT* era, but new data from *RXTE* and interesting results from the GBHC observations is providing new impetus. It appears that AGN variability shows great similarity to that of GBHC. Indeed, QPOs are the only important characteristic of Galactic binary variability that has not yet been established firmly in AGN. Population studies have shown X-ray variability to be strongly related to several other properties. The luminosity dependence - which may extend all the way down to GBHC - is indicative of a “universal” power spectrum that scales approximately with the length scale of the source. Much more data is required before this hypothesis can be firmly established, however. There is also a strong dependence of X-ray variability on spectral characteristics, in the sense that AGN with softer spectra - notably the subclass of NLS1 - are more variable. This remains unexplained, but clearly indicates that “Eigenvector 1” is related to something fundamental about the energy generation process. Detailed variability studies of some individual objects lends strong support to the idea that the emission mechanism for the X-rays is thermal Comptonization. In one source, NGC 7469, however, there is clear evidence that there is an additional variability mechanism on top of changes in the Compton seed. This must be related to the process that heats the Comptonizing corona, and apparently affects the hard X-rays more than the soft. Another intriguing phenomenon in this source is the observation

of a dramatic increase in the X-ray variability amplitude at the time when the spectrum is hardest - in contrast to the behavior observed when comparing objects. This may be related to some kind of instability, perhaps involving electron-positron pair production. Whatever the origin of these phenomena, it is clear that variability still has much to tell us about both the radiation mechanism and the dissipation process that causes active galaxies to emit X-rays.

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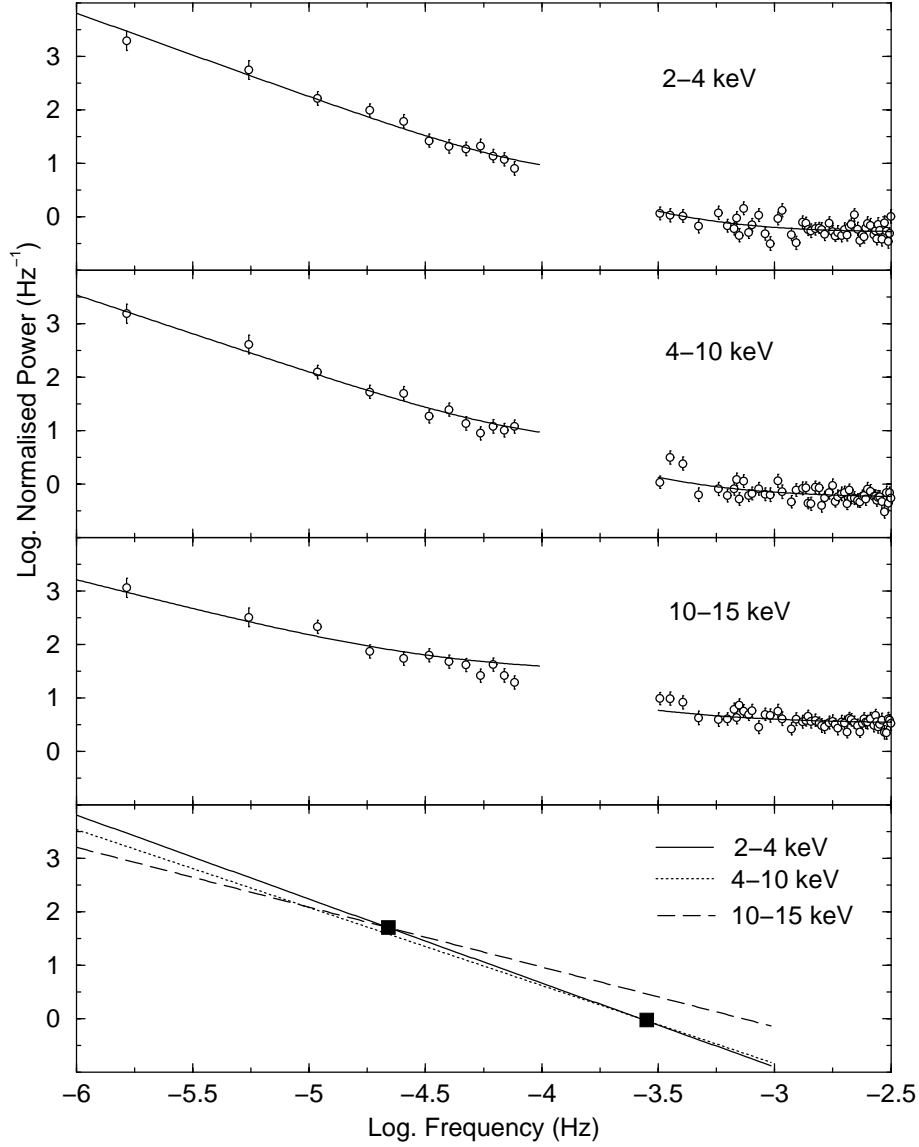


Fig. 6. PDS of NGC 7469 in three different energy bands (Nandra & Papadakis 2001). These were constructed in a two stage process, using the orbitally-binned data for the low frequency part, and an average of the intra-orbit 16s binned data for the high frequencies. The bottom panel shows the best-fit models to the PDS. These show that at low frequencies, more variability power is present in the soft X-ray PDS, which is consistent with the long-term variations being due to changes in the Compton seed. The PDS is *flatter* at higher energies, however, in contrast to the simplest expectations of Comptonization. On time scales shorter than about 1d, there is relatively more variability at high energies, implying another variability process, presumably related to the coronal heating mechanism, dominates the most rapid variations.